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THICKNESS EFFECT OF DCB SPECIMEN ON INTERLAMINAR FRACTURE TOUGHNESS IN CARBON/EPOXY COMPOSITES

P. ASHOK KUMAR[1], P. RAVINDER REDDY[2] & AVSSKS. GUPTA[3]

[1]Research Scholar, Department of Mechanical Engineering, Jawaharlal Nehru Technological University, Hyderabad, Telangana, India

[2]Professor & Principal, Chaitanya Bharati Institute of Technology, Hyderabad, (Osmania University Hyderabad), Telangana, India

[3]Professor, Department of Mechanical Engineering, JNTUH College of Engineering, Hyderabad. Telangana, India

ABSTRACT

In this work, the influence of specimen thickness on interlaminar fracture toughness in delamination of unidirectional carbon/epoxy laminates is presented. Specimens of three different thicknesses: 3.99, 5.27 and 6.65 mm are tested under the quasi-static condition to measure interlaminar fracture toughness G_{Ic}, in terms of strain energy release rate. It is found that higher fracture toughness values are obtained from thinner DCB specimens. While the G_{Ic} initiation values are dependent on the specimen thickness, whereas the propagation values of G_{Ic} increased continuously with crack length. Analysis of test specimens in mode I fracture is made by using three data reduction schemes based on modified beam theory, a compliance calibration method, and a modified compliance calibration method. Fiber bridging is also identified during experiments which lead to higher G_{Ic} in thin specimens.

KEYWORDS*: *Carbon/Epoxy, Delamination, Interlaminar Fracture Toughness, Mode I Fracture & Quasi-Static Condition

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Original Article

INTRODUCTION

The specific damage of high-performance laminated Composites is of particular interest because of their use of crash safety structures for aerospace and marine. Improvement in design, materials, and manufacturing enhances the usage of composite structures. Hence, it is utmost important to reduce the failure of laminated composites in design. One of the most common failure mechanisms in laminated composite structures is interlaminar delamination also known as debonding of adjacent lamina [1]. Generally, crack development in multidirectional composites causes mixed mode fracture which is enumerated by different crack propagation scenarios [2,3]. Mode I interlaminar delamination is the weakest fracture mode in case of laminated composite materials. The fracture toughness values in unidirectional composites are measured by a standard test procedure [4]. Last 30 years, a lot of work was concentrated on assessing how critical energy release rate, G_{Ic} depends on crack length, the width of the specimen [5], a thickness of specimen [5-7]. Results obtained in some early experiments by using compliance calibration methods indicated that the fracture toughness did not depend on the specimen thickness in unidirectional DCB [5-7]. Many authors showed that the propagation values of fracture toughness G_{Ic}, increases with increasing laminate thickness [7-9] whereas both Phillips et al.[10] and Kravchenko et al.[13]

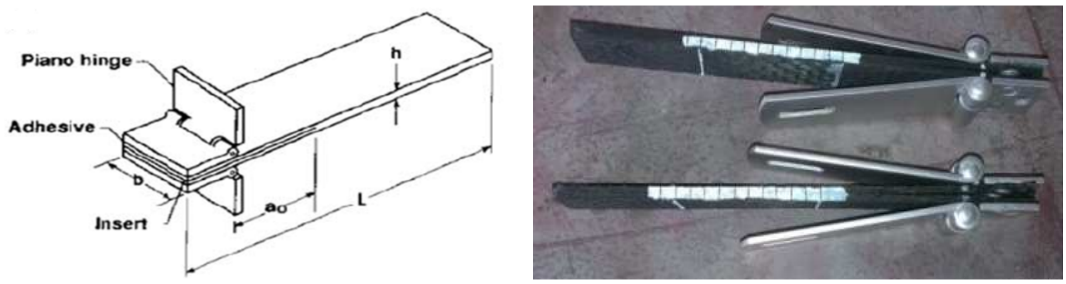
concluded that interlaminar fracture toughness decreases as the laminate thickness increases. So, in order to measure the initiation and propagation values of fracture toughness, the data reduction methods such as a modified beam theory or compliance calibration methods recommended by ASTM standard [4] were used by considering the finite rotation which occurs at the crack front. Some authors suggested that fiber bridging is also responsible for the increase in ERR with the crack propagation before reaching a steady-state value in mode I condition [7-11]. Farmand-Ashtiani et al.[12] observed that the R-curve depends on the specimen thickness in a carbon fiber laminates. Therefore, it is necessary to understand how this parameter influences the crack propagation.

Hence, in the present study, three different thicknesses of DCB specimens were prepared from a carbon fabric of 300 gsm and tested under the quasi-static condition to characterize the influence of specimen thickness on the mode I interlaminar fracture at the crack initiation and propagation in carbon/epoxy composites.

EXPERIMENTAL PROCEDURE

Materials and Specimen Preparation

A carbon fabric of 300 gsm and Lapox L-12 epoxy resin and a hardener (K-6) are used to fabricate unidirectional composite laminates. Specimens of different thicknesses are produced by a hand lay-up method. The laminates are allowed to cure at room temperature for 14-24 hrs. A Teflon film of 20 µm thickness is placed in the middle of the laminate during the lay-up process to act as an initial delamination. Finally, DCB specimens are cut from the panels using a diamond saw into 20 mm wide by 150 mm length beams with an initial crack length of 50 mm demonstrated in Figure 1. Edges of the specimen are ground to make clear visibility of the image of the crack tip position during testing. Specimens with Aluminum hinged clamps are used, with the hinged clamps bonded to both specimen faces with Araldite epoxy adhesive. During testing, the load is applied through these clamps. Test specimen edges are painted white and marked with red thin lines at every 5 mm from the tip of the insert to observe the crack propagation. The loads and corresponding load point displacements are recorded at these marks. In this work, tests are performed on three specimens per each thickness.



(a) **(b)**

Figure 1: Double Cantilever Beam Specimen

Test Procedure

For testing, the Specimens are firmly clamped in the Jaws of Instron machine as in Figure 2. Specimens are loaded through these clamps at a constant displacement rate of 0.5 mm/min during testing. The crack propagation is allowed for 5 mm intervals. At every 5 mm interval, the load and corresponding crack opening displacement are recorded by careful observation of specimen edges with a help of 3 LED Hand -held magnifier lens. This is continued till it reaches a crack propagation length of 50 mm from the starter crack. The load versus corresponding displacement plot is recorded by a computer. The failure load for each case is used to determine the mode I critical energy release rate G_{Ic}.

Figure 2: Experimental Setup for DCB Test Specimen

CALCULATION OF INTERLAMINAR FRACTURE TOUGHNESS, G_{IC}

In order to assess the interlaminar fracture toughness, $G_{Ic,}$ the experimental data should be analyzed by three methods described by ASTM standard D5528-13 [4] such as a modified beam theory (MBT), a compliance calibration method (CC), and a modified compliance calibration method (MCC) are as follows:

$$G_{Ic} = \frac{3P\delta}{2b(a+|\Delta|)} \tag{1}$$

where $|\Delta|$ is the correction for the delamination length, which takes care of the effect of the rotation at the crack front.

$$G_{Ic} = \frac{nP\delta}{2ba} \text{ with Berry's compliance calibration : } C = \alpha a^{n} \tag{2}$$

$$G_{Ic} = \frac{3P^2C^{2/3}}{2A_1bh} \text{ here } A_1 \text{ has to be determined by } (a/h) = A_1 C^{1/3} \tag{3}$$

Furthermore, experimentally obtained compliance values are used to calculate the curve fit parameters involved in these methods. In this work, the toughness values, $G_{Ic,}$, are measured by using above three methods and Resistance curves are depicted by using MBT and MCC methods only.

EXPERIMENTAL RESULTS AND DISCUSSIONS

The typical load-displacement curves obtained for the specimens of each thickness were displayed in Figure 3. It was observed that there is a small variation in the critical load for 3.99 and 5.27 mm thick specimens, but the considerable variation is found for 6.65 mm thick specimens. Overall crack propagation was stable. Figure 3 shows that the load increased after initiation depicting very pronounced R-curve effects. Compliance of DCB specimens are calculated from the load – displacement plots obtained experimentally for specimens of different thicknesses was illustrated in Figure 4. It was depicted from Figure 4 that compliance values different for different specimen thicknesses. The mode I delamination fracture toughness values in terms of the critical energy release rate was determined based on data reduction methods for each specimen thickness shown in Table 1, Table 2 and Table 3.

The Resistance (R - Curves) curves for UD specimens of different thicknesses obtained by using MBT and MCC methods were shown in Figure 5. It was seen from R-curves that the strain energy release rate G_{Ic}, at crack initiation was considerably high value for 3.99 mm thick specimens compared to 5.27 and 6.65 mm specimens. Further, G_{Ic} values increase at subsequent crack growth with the decrease in thickness of specimen. Comparison of mean values of G_{Ic} for different thicknesses as shown in Table 4. From the plots shown in Figure 5, it was observed that there is a continuous

increase in G_{Ic} values as the crack propagates up to a delamination length of 85 mm followed by steady-state values, especially the final propagation values, in each specimen. Further, the G_{Ic} values for thinner specimens have slightly higher values than the G_{Ic} values for thicker specimens as seen in Table 1, Table 2 and Table 3. This was due to fiber bridging phenomenon in which migration of fibers between delaminating plies occurs and leads to additional energy dissipation during crack propagation [14]. It was also noticed here that the decreasing amount of fiber bridging with the increase in specimen thickness. Side views of specimens with different specimen thicknesses were displayed in Figure 6. However, to fully understand this thickness effect on G_{Ic}, parametric FE modeling is employed to measure these values and then compared with experimental results.

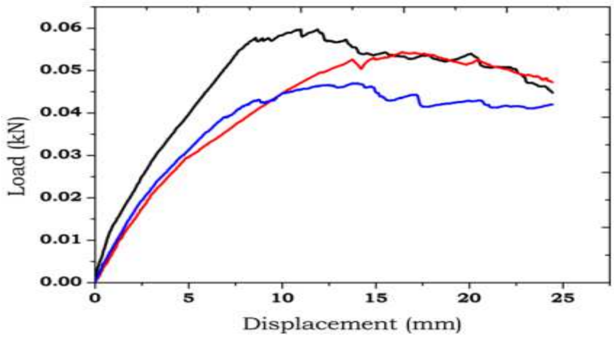


Figure 3(a): The load-Displacement Behavior of a DCB Specimens with $[0]_{16}$ Specimen of Thickness h=3.99 mm

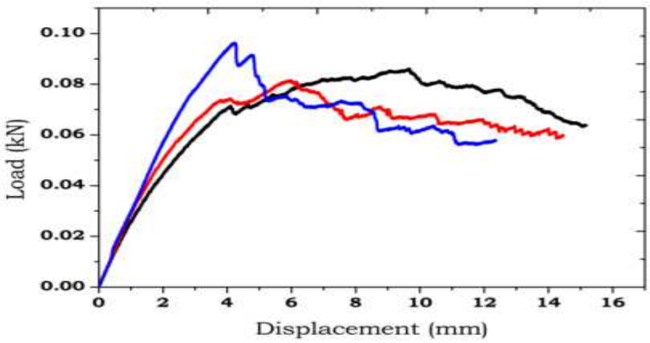


Figure 3(b): The load-Displacement Behavior of a DCB Specimens with) $[0]_{20}$ Specimen of Thickness h=5.27 mm

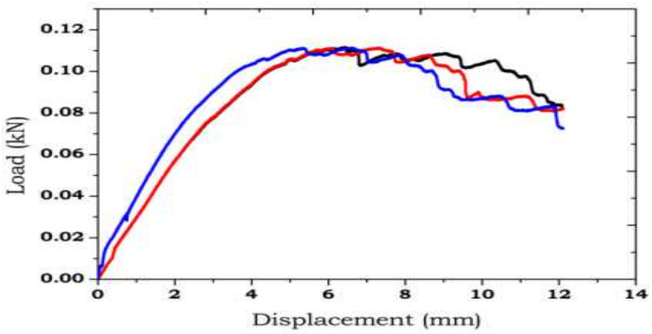


Figure 3(c): The load-Displacement Behavior of a DCB Specimens with $[0]_{24}$ Specimen of Thickness h=6.65 mm

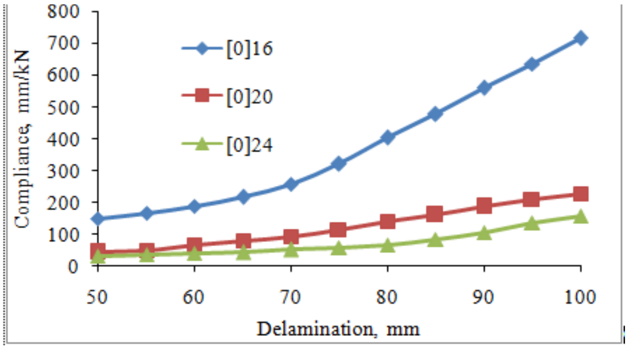


Figure 4: Compliance for Different DCB Specimens

Table 1: G_{Ic} Values Obtained from DCB Test for $[0]_{16}$ Specimen of Thickness, h = 3.99 mm

S.No	Displacement δ (mm)	Load P (kN)	Compliance δ/P	Delamination *a* (mm)	Width b (mm)	G_{Ic} (kJ/m^2) MBT	G_{Ic} (kJ/m^2) CC	G_{Ic} (kJ/m^2) MCC
1	4.75	0.0327	147.138	50	21.11	0.16976	0.18043	0.16672
2	6.85	0.0424	165.091	55	21.11	0.29929	0.31237	0.30548
3	8.68	0.0470	186.484	60	21.11	0.39383	0.40380	0.41055
4	10.68	0.0501	214.851	65	21.11	0.48018	0.48418	0.50923
5	13.25	0.0516	256.935	70	21.11	0.57390	0.56945	0.60873
6	15.79	0.0495	319.166	75	21.11	0.61839	0.60595	0.64608
7	18.55	0.0462	402.461	80	21.11	0.64226	0.62253	0.65683
8	20.86	0.0440	476.486	85	21.11	0.65205	0.62600	0.66478
9	22.81	0.0410	558.221	90	21.11	0.63292	0.60291	0.64184
10	24.74	0.0391	635.549	95	21.11	0.62480	0.59074	0.63588
11	26.76	0.0376	714.493	100	21.11	0.62136	0.58353	0.63546

Table 2: G_{Ic} Values Obtained from DCB Test for $[0]_{20}$ Specimen of Thickness, h = 5.27 mm

S.No	Displacement δ (mm)	Load P (kN)	Compliance δ/P	Delamination *a* (mm)	Width b (mm)	G_{Ic} (kJ/m^2) MBT	G_{Ic} (kJ/m^2) CC	G_{Ic} (kJ/m^2) MCC
1	2.282	0.0555	41.440	50	21.09	0.14388	0.15519	0.14672
2	3.555	0.0749	48.106	55	21.09	0.28127	0.29770	0.29504
3	4.763	0.0737	64.677	60	21.09	0.34442	0.35896	0.34952
4	5.901	0.0761	77.532	65	21.09	0.41181	0.42372	0.42021
5	6.994	0.0774	90.673	70	21.09	0.46530	0.47255	0.48063
6	8.514	0.0758	112.738	75	21.09	0.52393	0.52533	0.53359
7	9.746	0.0697	140.560	80	21.09	0.52302	0.51909	0.52368
8	10.845	0.0683	159.281	85	21.09	0.54171	0.53311	0.54770
9	12.157	0.0658	184.718	90	21.09	0.55572	0.54316	0.56083
10	13.020	0.0622	209.315	95	21.09	0.53613	0.52087	0.54449
11	13.962	0.0615	226.612	100	21.09	0.54297	0.52467	0.56164

Table 3: G_{Ic} Values Obtained from DCB Test for $[0]_{24}$ Specimen of Thickness, h = 6.65 mm

S.No	Displacement δ (mm)	Load P (kN)	Compliance δ/P	Delamination *a* (mm)	Width b (mm)	G_{Ic} (kJ/m^2) MBT	G_{Ic} (kJ/m^2) CC	G_{Ic} (kJ/m^2) MCC
1	1.693	0.053	32.371	50	21.16	0.10190	0.10336	0.10002
2	2.383	0.069	34.529	55	21.16	0.16393	0.16294	0.16930
3	3.335	0.087	38.332	60	21.16	0.27303	0.26557	0.29217
4	4.240	0.100	42.238	65	21.16	0.37031	0.35394	0.41050
5	5.373	0.107	50.406	70	21.16	0.46151	0.43495	0.51649
6	6.263	0.110	57.102	75	21.16	0.53470	0.49777	0.60760

Table 3: Contd.,

7	7.175	0.107	67.103	80	21.16	0.56824	0.52302	0.64184
8	8.321	0.102	81.935	85	21.16	0.59670	0.54389	0.67148
9	9.628	0.091	106.061	90	21.16	0.59350	0.53593	0.63843
10	11.180	0.083	134.687	95	21.16	0.59860	0.53674	0.61980
11	12.248	0.079	156.531	100	21.16	0.59279	0.52838	0.61024

Table 4: Comparison of G_{Ic} Mean Values for Specimens of Different Thicknesses (Standard Deviation in Brackets)

	Fiber layup	Thickness h (mm)	Modified Beam Theory(MBT)	Compliance Calibration(CC)	Modified Compliance Calibration(MCC)	Width, b (mm)
G_{Ic},(kJ/m²) (Mean values)	$[0]_{16}$	3.99(0.03)	0.51898(0.05)	0.50744(0.06)	0.53469(0.05)	21.11(0.02)
	$[0]_{20}$	5.27(0.09)	0.44274(0.03)	0.44312(0.02)	0.45128(0.03)	21.09(0.00)
	$[0]_{24}$	6.65(0.06)	0.44138(0.01)	0.40786(0.02)	0.47981(0.01)	21.16(0.04)

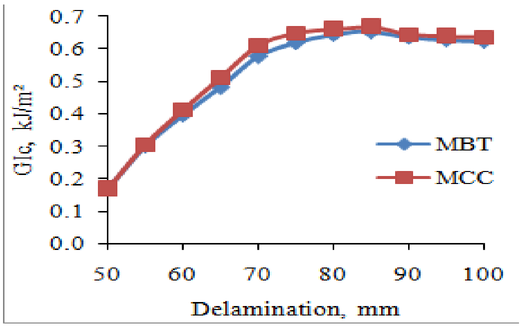


Figure 5(a): Resistance Curve (R-curve) for $[0]_{16}$ Specimen of Thickness, h=3.99 mm

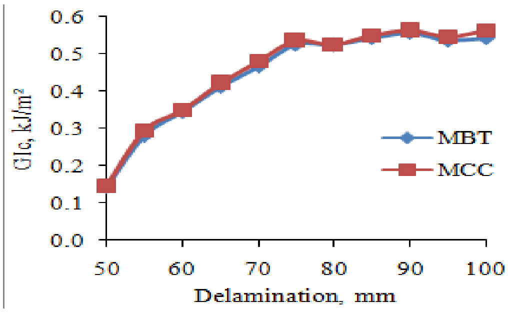


Figure 5(b): Resistance Curve (R-curve) for $[0]_{20}$ Specimen of Thickness, h=5.27 mm

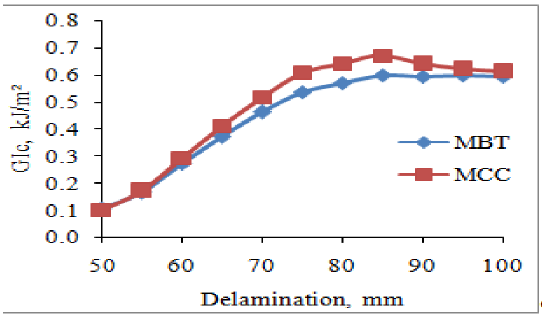


Figure 5(c): Resistance Curve (R-curve) for $[0]_{24}$ Specimen of Thickness, h=6.65 mm

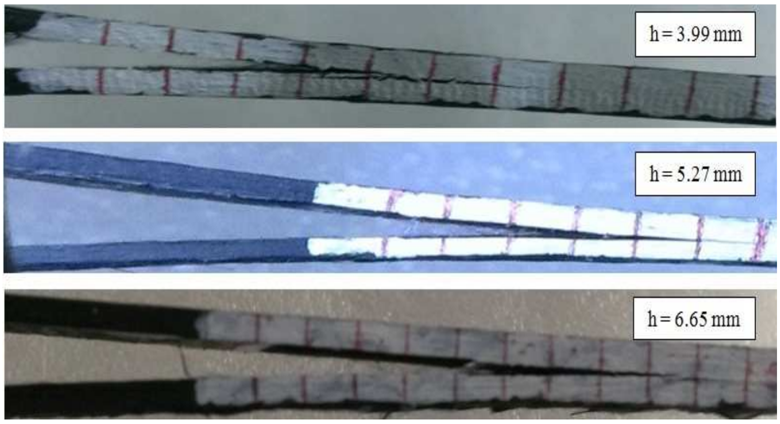


Figure 6: Formation of Fiber Bridging with Crack Growth for Specimens of Different Thicknesses

CONCLUSIONS

The thickness dependence of the mode I interlaminar fracture toughness $G_{Ic,}$ in unidirectional composites was investigated by using DCB specimens of different thicknesses. It was found that the initiation (first) value of G_{Ic} depends on the thickness of the specimen whereas the propagation values of G_{Ic} increased continuously with crack length. Higher G_{Ic} values were found for thinner specimens. Fiber bridging was also more prominent for thinner specimens. The plateau values obtained for thinner specimens were slightly higher than those for thicker specimens.

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